

Use of Fault Trees for Operations and Systems

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Use of Fault Trees for Operations and Systems

1. INTRODUCTION

A fault tree is a type of hazard analysis used to graphically show all the events and conditions that must occur in order for a specific hazardous event to happen. If the probabilities of all the conditioning events are known or can be reasonably approximated, a quantitative value for the hazard can be given. The graphical nature of the fault tree allows the reader to see the events that make up the hazard and concentrate on reducing the probability of major contributors. Fault trees are also especially adept at recognizing single-point failures.

Fault trees have been used in the government for a long time. The pioneer of the technique was in the safety analysis of nuclear reactors in the 60's¹. Many refinements have been made and the standardization of the symbols and process are firmly entrenched. With the incorporation of computer software, fault trees have become much easier to create, no longer requiring recopying whenever an error is found or an event added. Also, computers have eliminated the arduous process of calculating the probability of the top event by Boolean algebra.

Currently, fault trees are being used for both operations (movement of ton containers from CASY to the CTF²) and with systems (XM998 Smoke Grenades³) at ERDEC. The graphical presentation of the fault tree makes it effective for presentations and can be easily understood in a short period of time. This is a great improvement over forcing a person to go through pages of documentation to find the hazards. This type of analysis is important when a specific hazard probability is desired. The Army's requirement for safe and arm devices to have a failure rate of less than one in a million requires a quantitative hazard analysis.

2. FAULT TREE CONSTRUCTION

The process of constructing a fault tree involves three major steps; problem definition, brainstorming, construction. This section describes how the ERDEC Safety Office performs fault trees using an example of getting to work on time.

The first step is to define the problem and come up with a top event. The top event is the condition which you are trying to avoid, for instance "Failing to Get to Work on Time". This event is important because the results will be directly related to the top event. If the top event is poorly worded or too broadly focused the fault tree may wonder to inconsequential events and wasted time.

The second step in constructing a fault tree is the brainstorming step. This is the most important and most critical step. At this point you do not need to use fault tree symbols or construction, focusing on putting thought on paper is the most important thing at this time. One effective method is to gather a diverse group of technicians and managers and brainstorming probable situations that refer to the top event, for instance, flat tire, stolen car, or crash. You should try to work on the level under the top event until it is completely exhausted (figure

Accident

- Other driver cuts you off
- Bad Weather
 - Snow, rain, tornado
- Brakes Fail
- Not paying attention
 - Talking on phone

Figure 2

1). Trying to work on second and third levels early impedes the brainstorming process. Once you have exhausted failures you can focus on faults and/or conditions that would be required for the failure to occur, such as other driver cutting you off and your inability to avoid other car (figure 2). Continue brainstorming each failure until you get to a point where you have measurable events or conditions that can be assigned a value.

Failing to get to work on time

- Flat tire
- Accident
- Traffic Sleep
- Car stolen
- Run out of Gas
- Over

Figure 1

Once you are satisfied that you have completely investigated the problem. You can focus on developing the tree (figure 3). The rules for fault trees are clearly established and can be found in many of the references at the end of this report.

Construction of the tree is followed by assigning values to the events that do not have a concrete probability or frequency. Perhaps the most difficult probabilities are related to human error, human factors table are available for many common tasks⁹, however many times you have to use your best judgment.

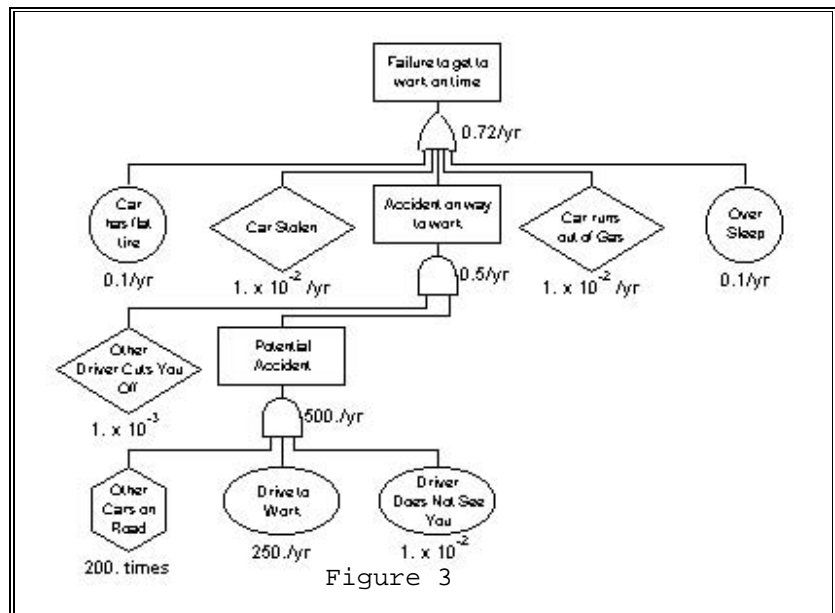


Figure 3

At this point statistics can be calculated and results are now apparent. For our example, we can expect to be late for work just less than 1 day every year. We can also expect to get into an accident once every two years. Fault trees also allow you to change the numbers any time a more accurate statistic is known.

3. USE IN SYSTEMS

Background

In order to determine the hazardous conditions associated with the safety and arming device of the XM998 Smoke Grenade (figure 4) a complete Fault Tree Analysis (FTA) was performed. The hazard analysis was conducted to arrive at an estimate of the safety system failure rate and to identify any single-point or credible failure modes, as stated in MIL-STD-1316D⁴. Specifically, the FTA looks for ways the XM998's Safe and Arming Device can fail, allowing the grenade to function unintentionally. The analysis looks at the entire life of the system and all stages of use: storage, transporting, chambered, loading, handling, and demilitarization. The analysis considers the consequences of the faults and assigns risk to each hazardous scenario.

Each scenario may not result in injuries, i.e., if a grenade functions with no one around you have a hazardous situation but no damage.

The XM998 uses a proven basic design and much is known about the safety and reliability of most of its components. Many tests have been conducted on the components of the round to demonstrate the effectiveness of its safe and arming device. These facts are not normally known when conducting fault trees; however, there is no reason to ignore them. As a result of this, the fault tree may skip hazards that would be mitigated by proven safety features.

The quantitative inputs into the fault tree are products of testing, analogy, and sometimes using best guess. This is an unavoidable problem when dealing with fault trees. In most cases, this analysis uses the most conservative numbers in order to give the worst case scenario. When reading the results of the fault tree, you may take any event and say that the probability of that event occurring is equivalent to the corresponding number.

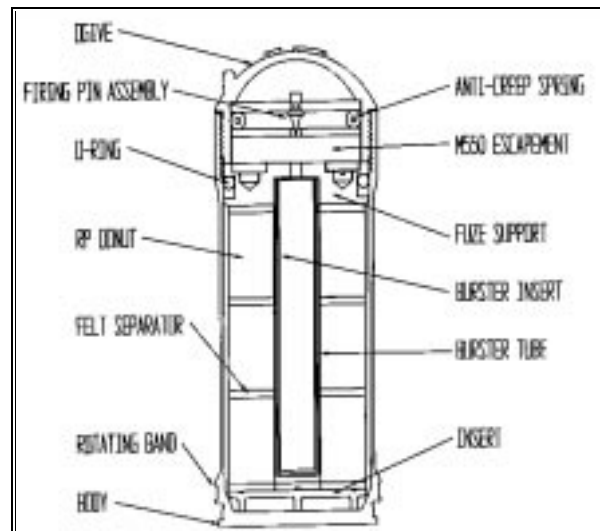


Figure 4

2. Assumptions

1. Testing performed is representative of the real world.
2. Basic human errors occur without any misguiding indicators.
3. All drops are considered to be six foot drops.
4. In the absence of actual failure probabilities the event was broken into three categories with the corresponding probability.
 - a. Extremely Improbable (1×10^{-9}) - Not considered credible.
 - b. Improbable (1×10^{-6}) - Not likely to happen in the life of the project.

- c. Credible (1×10^{-3}) - May happen to several rounds in the life of the project.
- 5. The probability for human error is taken to be 1×10^{-3} . This number is generally accepted in industry as conservative for common tasks with trained personnel.
- 6. Supporting equipment is in good condition and operated in accordance with standard procedures. Failure for supporting equipment is 1×10^{-6} .

Definitions:

- 1. Function - The payload of the grenade is dispersed due to ignition of the central burster.
- 2. Ignition - The propellant in the M195 cartridge case is triggered.
- 3. Fired - The round is ignited and expelled from the tube.

3. Fault Tree Analysis

Five states have been developed as possible areas that an unintentional functioning of a round may occur. The severity of a round functioning in each of these states differs from critical to marginal. The probability of an unintentional functioning of a round has been estimated at 2×10^{-8} . This is equivalent to saying that one round in every fifty million will have some part of it fail and function or ignite unintentionally. The probability of safe and arm failure is estimated at 7×10^{-9} , less than one in every hundred million rounds will have an in-line fuze. The hazard associated with the use of this round is more accurately seen when each of the states is analyzed. Each of the scenarios come directly from the fault tree located in Appendix A. The five states are as follows:

A. Functioning During Handling/Transporting/Storage of Packaged Rounds

This state includes any condition that occurs while the round is still in its packaging. The packaging is subject to testing to determine the severity of many of the scenarios. The tests that were conducted include drop, fire, containment, and out-of-line detonator test. Most of these tests do not give statistical data because of the low number of trials. However, general theories can be made. Also, these tests have specific criteria for passing, they may pass a round when a hazardous condition exists, i.e., a drop will not cause the round to function but the escapement system may break and move the detonator in-line with the firing pin.

The packaging is designed to prevent the round from functioning and contain much of the hazardous energy. This mitigates many of the hazards associated with inadvertent functioning while packaged. In order for a hazardous condition to exist when a round functions, the package integrity must be compromised. The scenarios that would test the packaging would include:

Scenario 1: Dropping the container and having a round function. This could only occur to a normal, out-of-line fuze, if one of the following events took place. First, the shock from the drop causes the burster to detonate. The burster is insensitive and extremely unlikely to function upon dropping. Second, a drop could cause the detonator to function and if the output of the charge propagates to the burster the grenade would function. The test for this has been performed and a grenade that is fully out-of-line will not allow propagation to the burster.

Risk Assessment: The functioning of a round inside the container should not allow fragments to exit unless the top is open. During handling, the top will not be open under normal circumstances. The severity would be considered **negligible** and its 1×10^{-9} probability is **improbable**. The risk associated would be **low**.

Scenario 2: Dropping a container with an in-line fuze is another way the round could function. The method for the fuze to become in-line is left in this section as undeveloped. A full description of a fuze becoming in-line is in Section 4. When coupled with a drop an in-line fuze may allow functioning. The rounds are packaged in such a way that if the package hits on either of the two sides, the firing pin may strike an in-line fuze and cause the round to function.

Risk Assessment: Once again the functioning of packaged rounds should not allow fragments to exit unless package integrity is compromised. If rough handling or long storage was the reason for the fuze to become in-line, the degraded packaging may allow fragments to escape. The severity is still **negligible** and a probability of 3×10^{-5} is **credible**. A **low** risk level is connected with this scenario.

Scenario 3: A direct or indirect lightning strike could cause the round to function. A lightning strike is always improbable and most of the time the package is under a cone of protection. The round should pass the test for lightning strikes as packaged.

Risk Assessment: The hazards associated with a lightning strike would be greater than the fragments possible with functioning grenades. It is **improbable** that a lightning strike will be seen and cause a round to function, 1×10^{-15} . The additional hazard would be **marginal**. The corresponding risk is **low**.

Scenario 4: Fire in a storage facility is one of the tests conducted on the packaging container. It is unknown if fragments will escape the packaging during a fire or merely burn. The fragments associated with a fire is unlikely to cause must more of a problem than the fire itself. Packaging test will be conducted in order to get the proper hazard classification.

Risk Assessment: As with the lightning scenario, the danger to personnel would be more affected by the fire than a functioning containerized round. Since the package will contain most of the fragments the increased severity would be **marginal**. The probability is **improbable** and the risk is **low**.

Scenario 5: The XM998 is a standard round and may be stored with other types of munitions. The functioning of an adjacent munition may produce fragments penetrating the packaging material. A direct hit to the burster may cause functioning. This scenario would also include munitions fired at positions storing rounds.

Risk Assessment: The round will not be subjected to the bullet impact test, however no functioning would be expected. Fragments escaping the packaging is not considered a credible

hazard. The additional risk would be **low** since the additional severity is **negligible** and the probability is **improbable**.

Scenario 6: Pyrotechnics have the possibility of spontaneously igniting. If rounds are subjected to excessive heat, the ignition temperature could be reached. At this temperature the round could function without any other external energy. Moisture from rain or high humidity that enters the pyrotechnic burster could destabilize the round and allow functioning with normal handling.

Risk Assessment: Even in the **improbable** event that the propellant ignites spontaneously, the round would not leave the packaging container. Hence, the severity is **negligible** and the risk is **low**.

Scenario 7: A package may be compressed enough to cause functioning. If a vehicle runs over a package, the rounds may function. The energy released from the rounds will probably not effect a vehicle of the size required to compress the package instead of pushing it. Also, if the round is crushed, its structural integrity is compromised and it probably will not be able to hold the pressure required for the burster to function properly.

Risk Assessment: The effects of a packaged round functioning under a tank or other military vehicle would be **negligible**. The likelihood of a container being run over by a vehicle is **improbable** hence the risk would be **low**.

B. Functioning While in the Launcher

Once the round is loaded in the launcher, it is susceptible to faults from the M203 grenade launcher. This analysis tries to not include faults from the launcher, however, it is assumed that a launcher fault is one in a million. Two different hazards can be associated with a loaded round. First, the round expels from the tube toward an uncleared area. This is particularly hazardous due to the likelihood of nearby people and equipment. Second, if the round functions inside the barrel of the launcher, in-bore firing. A set of scenarios has been developed for these hazards as follows:

Scenario 1: Electrical spark hits the propellant causing an ignition in the M195 cartridge. This could be caused from a static buildup of electricity under normal movement and the firing of bullets. However, since the weapon is bonded to the human carrier, static is unlikely to be a problem.

Risk Assessment: A spark created with the normal use of the weapon would be unlikely to hit the exact spot required for the propellant to ignite. This combined with the unlikely spark generation hazard gives a probability considered **negligible** but the severity is **critical** due the possibility of a round functioning in close proximity with its human carrier. The risk is **low**.

Scenario 2: The propellant could be struck by other than normal means resulting in an early firing. The striking could be a direct result of dropping the weapon and causing the hammer to strike the round. Other weapon faults could also cause the propellant to be triggered. These are all grouped together on the fault tree.

Risk Assessment: Since the weapon is a standard item its safety is given and not considered in this report. The round itself does not have to be at fault for this scenario to occur. The probability is **remote** and the severity is **critical**. The risk equates to **medium**. This risk is associated with the weapon and not the round. The round adds little to this scenario and no changes can be made to the round to decrease the risk.

Scenario 3: If a round is chambered with an in-line fuze, firing can result in an immediate functioning. The pressure associated with propelling the round out of the tube may be sufficient to simulate impact and allow the firing pin to stab initiate the detonator. This would cause the round to function in-bore and the operator would be vulnerable. The description of how a fuze can be in-line is in Section 4.

Risk Assessment: A round functioning inside the launcher may injure the soldier and similar occurrences have resulted in death, a **catastrophic** hazard. The probability of having an in-line fuze chambered in the round is low, but likely to happen in the lifetime of the system. The inspection process involves three independent inspections at the factory, prior to assembly, and an X-ray after assembly. Even using the human error rate of failure, 1×10^{-3} , the probability is **improbable**. The risk is **medium**.

Scenario 4: If a round is struck by a bullet, fragments, or lightning, it may function. The penetration of the round can cause the burster to function. However, the soldier is likely to be in greater danger from the source of the fault rather than the round functioning.

Risk Assessment: When considering the reasons for the round fault, lightning strikes, bullets, and munition fragments, the severity of the round functioning is **negligible**. It is also **improbable** that the round could function under these conditions. The additional risk is **low**.

C. Functioning During Loading

The loading of rounds is guided by the launcher's operation manual. Under normal circumstances, following this operation manual virtually guarantees safe operation. However, abnormal situations or failure to follow the guide could result in premature firing. Two scenarios have been determined to allow ignition of the round during loading.

Scenario 1: If a spark is generated when the launcher is closed with a loaded round, the primer may ignite and expel the round from the tube. No spark is normally generated and the size of a spark is extremely unlikely to cause the primer to ignite. Heat generated from this spark is also unlikely to cause a problem.

Risk Assessment: A round functioning on loading poses a **critical** hazard due to the proximity of personnel and equipment. The probability is **improbable** and the risk is **low**.

Scenario 2: If the tube is not cleared before loading the round, a foreign object may hit the primer on the M195 cartridge case, simulating a hammer strike and launch the round. The design of the round and launcher preclude this from being a plausible scenario.

Risk Assessment: Foreign objects should be cleared from the tube before loading. Even if the operator fails to clear the tube properly, the probability of ignition is still **improbable**. The severity is again **critical** due to the proximity of personnel and equipment. The risk is **low**.

D. Functioning During Handling

Handling of unpackaged rounds is the most hazardous time for the XM998 grenade. The soldier exposes the round to a much wider range of environments. The round is subject to weather, heat, and water all while being positioned in close proximity to the soldier. Two scenarios are cited for when a soldier is handling the round.

Scenario 1: If the unpackaged round is dropped during loading or anytime during the life of the round there is a chance of firing. The round is tested for dropping, however, if the round is compromised with an in-line fuze due to a previous fault the round may function, Section 4. If the round is dropped on the ogive or base, it can cause the firing pin to strike the detonator.

Risk Assessment: There is a **remote** chance of a six-foot drop causing the round to function, due to the safe and arm device of the round. Injury of the worker would include fragments from the projectile hardware, burning from the disseminated RP, and smoke inhalation; **critical** severity. The risk is **medium**.

Scenario 2: Exposing the round to excessive heat and moisture could cause spontaneous functioning of the round. If rounds are subjected to excessive heat, the ignition temperature could be reached. At this temperature the round could function without any other external energy. Moisture from rain or high humidity that enters the pyrotechnics could unstabilize the round and allow functioning with normal handling.

Risk Assessment: It is an **improbable** event that the primers or propellants could ignite spontaneously. The severity is **critical** due to the proximity of the soldier to the grenade. The risk is **low**.

E. Functioning During Demilitarization

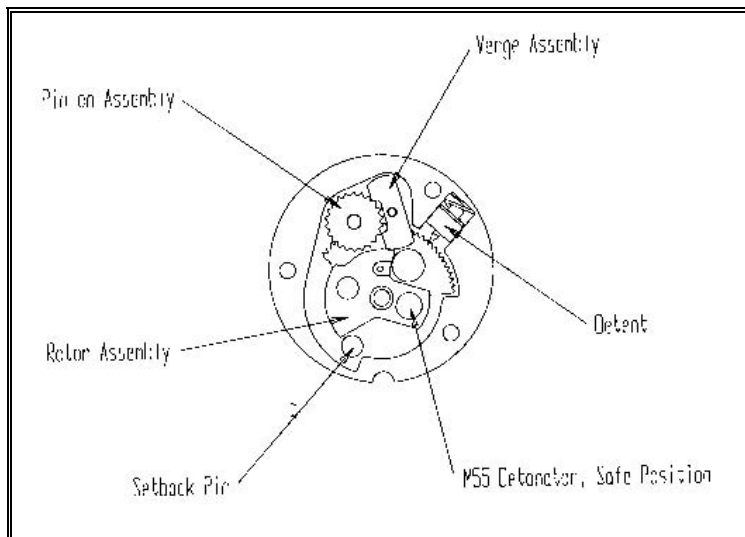
Demilitarization procedures have been established for the XM998 grenade. The procedures call for more than sufficient safety practices for disposal of this grenade. This is still an inherently dangerous procedure and a spark from static build up on the conveyor or a fault in the deactivation furnace could allow hazardous energy to escape from engineering controls. The only nonstandard procedure is the removal of RP from the round, which is not extremely hazardous.

Risk Assessment: The demilitarization process was designed for high explosive rounds that pose a much higher danger. The process limits the severity of a round functioning to **marginal** while keeping the probability at **remote**. The risk is **low**.

4. In-Line Fuze Analysis

The M550 Escapement Assembly can become in-line from a number of events. The safety devices on the assembly require most of the faults to be a combination of many failures. Having an in-line fuze is the driving force behind most of the hazard associated with the use of the round. Any effort reducing the possibility of an in-line fuze increases the safety of the overall grenade.

The only single-point failure is the incorrect assembly of the round in such a way that the detonator is in-line with the firing pin. Inspection of all rounds is performed to ensure that this fault does not occur. Physically, there is nothing to stop the escapement from being assembled with an in-line detonator except the skill of the worker. The inspection process uses three independent inspections. The first is at the factory where the M550 is fabricated. The second is prior to assembly of the XM998. The third is an X-ray inspection after the round is assembled. The probability of a in-line fuze getting through each inspection has been expressed as one in a million, 1×10^{-6} , making the overall failure rate 1×10^{-18} . Since this is a catastrophic failure the associated risk is medium.



If the assembly of the round is performed correctly, a combination of events must occur to have an in-line detonator. A common fault for all following scenarios is the failure of the setback pin. The setback pin can fail by either having the pin snap or having the setback spring fail, allowing the pin to fall out of safe.

Breaking of the setback pin is not likely to occur under normal circumstances. It is extremely unlikely that a good pin would break if the round is dropped, no test data was found for this scenario but it was assumed to be extremely unlikely for a six-foot drop. If the pin has deteriorated from water, humidity, or the generation of phosphoric acid from the payload, the probability of a pin breaking on a drop is greater.

If the setback pin fails, one of the following combinations must occur to allow the detonator to move freely and become in-line: rotor teeth fail, detent/detent spring fails with pinion failure, or detent fails with verge failure. If the detent fails by itself, the rotor will rotate with gravity or normal jostling to the armed position.

The rotor teeth provide the locking mechanism for the detent safety system as well as a part of the delay. Failure of the teeth will result in a freely moving detonator if the setback pin fails. The teeth could corrode and break if allowed to rust and deteriorate. Also if incorrectly installed, the teeth may not contact the detent and pinion systems.

Detent failure can occur by failure of either detent pin or detent spring failure. If water or phosphoric acid is allowed in the escapement the spring or detent could corrode and break. After long storage, the spring could fatigue and cause the detent to lose contact with the rotor teeth. The spring or detent could be installed improperly or left out of the assembly all together. Any of these failures with a setback pin failure would allow limited movement of the detonator or free movement with a pinion or verge failure.

The pinion and verge work together to act as the delay mechanism. If one of these systems fails, there will be no delay and the grenade will be armed almost immediately after firing. This should not cause a hazardous condition under normal circumstances, but it is one of the safety devices used in the grenade. If the setback pin and detent fail, pinion or verge failure will allow for free movement of the detonator. The detonator will be in the in-line position whenever it is rotated in the clockwise direction or when in-line is the lowest potential energy state. The pinion and verge systems are subject to incorrect assembly, corrosion from water, phosphoric acid, or reaction between differing metals.

5. Results

A. Hazard Analysis

All the hazards associated with faults of the XM998 grenade are low except for three mediums. The first is a fault by the weapon causing a round to be fired prematurely. This is a single point failure on the part of the weapon, for which the reliability was not researched for this analysis. The probability may be lower and the hazard may in fact be low. The second hazard is for firing a round with an in-line fuze. Again, this is a single-point failure and if a round is loaded with an in-line fuze, in-bore functioning is probable. The final medium hazard is dropping a round

during out of package handling. This is particularly hazardous if the round is in-line, since out-of-line tests show no propagation to the burster.

There is really no solution to mitigate the medium hazards, when there is a need for a system that containing sufficient energy to result in catastrophic failure; no probability will result in a low hazard.

B. Sensitivity Analysis

Since the fault tree process is inherently flawed when using quantitative data, it is important to know the upper and lower bounds of risk. While the numbers use the best knowledge currently known, there is a possibility that future events will change the numbers in a positive or negative manner. This is especially critical when dealing with single-point hazards. If future events result in knowledge that the round is susceptible to a fault at a higher rate than described on the fault tree, that number should be plugged in to see how the overall safety is effected. For instance, if the assembly of rounds show a high rate of error such that an in-line fuze has a higher possibility of occurring, many of the hazards would probably become high.

6. Conclusions

The XM998 grenade is safe considering its use of explosive and pyrotechnic materials. The safe and arm device mitigates the hazards associated with basic handling and operation. There are very few single-point failures and many of the failures shown on the fault tree are not considered credible. Many of the failures cannot be stopped by any safe and arm device and the hazard associated with the fault is greater than the grenade failure, notably fire, lightning, and fragments from other munitions. Since the safe and arm device used for the XM998 has been used in other systems, any change would increase the hazard by reducing the confidence in its design. Overall, the safe and arm device used for the XM998 grenade is the best available.

4. USE IN OPERATIONS

Background

This hazard analysis looks at the risks involved in the transportation of twenty-seven ton containers (TCs) of Mustard Agent (HD) on flatbed trucks from the Chemical Agent Storage Yard (CASY) to the Chemical Transfer Facility (CTF). A risk assessment was desired to help determine the safest way to transport the chemical and any specific hazards that needed to be focused on. Two methods have been proposed, moving all the TCs separately or up to four at a time on the flatbed trucks. An accurate assessment is needed due to the proximity of housing to the route between the two facilities. A worst case scenario need to be described in order to ensure safety for personnel at Edgewood.

Risk of transporting 1 ton container

Probability

A fault tree analysis was performed to determine the probability of a release from a TC during transport. In Appendix B, Figure 1, the fault tree shows that in order to have a release from a TC any of the following three events must occur:



1. TC is dropped releasing agent. There are three possible situations in which TC can be dropped. They are: (i) Drop from crane or (ii) Fall from vehicle during transport, or (iii) Drop while unstacking.

(i) As shown on the far left of Figure 2 of Appendix B, a crane is only used during loading and unloading, and a release is only possible if a TC is dropped from sufficient height to cause the shell to fail. Any of the following events must occur if a TC is dropped:

(A) Crane fails during lift. This event would happen as a result of the combination of (i) failure of major component of crane and (ii) improper inspection and testing of equipment. The former event is an equipment failure and has a probability of 1×10^{-3} . The latter event is human error and therefore has a probability of 1×10^{-3} .

(B) Cable breaks during lift. The combination of events: (i) cable being weakened and (ii) failure to maintain and test regularly, will lead to the possible break of the cable. The former event is an equipment failure and the latter event is human error, therefore they each have a probability of 1×10^{-3} .

(C) Improper attachment to TC. This failure is a combination of three possible events: (i) Failure to follow procedures (ii) Improper attachment and (iii) Failure to inspect attachment. All three of these are human errors and therefore have a probability of 1×10^{-3} .

(ii) The middle of the fault tree in Figure 2 of Appendix B showed the event in which a TC falls from a vehicle during transport. As illustrated, the fall is only possible if 1) Straps fail to hold TC and 2) Speed is high enough for movement of TC. There are two ways in which straps can fail to hold TC. They are:

(A) Straps are applied incorrectly. This is a combination of failure to follow procedures, failure to inspect straps and attachment unable to hold TC. These are human errors and an equipment failure and therefore have a probability of 1×10^{-3} .

(B) Straps break during transport. Straps are broken as a result from either tension on straps exceeds limits or weak or cut straps are used. One is an equipment failure and one is a human error and therefore have a probability of 1×10^{-3} .

(iii) Referring to the far right of the fault tree in Figure 2 of Appendix B, a TC releases agent during unstacking only if “TC falls during Unstacking” and “the fall must have sufficient impact energy to cause breakage”. Fall of TC during Unstacking can result from two conditions:

(A) TC is placed on unstable holder. As illustrated in the figure, such unstable condition is caused by failure to setup the holder properly or failure to check ground stability. These are human errors and have a probability of 1×10^{-3} .

(B) Improper placement of holder by workers. This is a human error and has a probability of 1×10^{-3} .

2. Leak of Agent from TC. As shown in Figure 1, Appendix B, a leak can be caused by the move of TC or if a leak already exists (Probability: 5.9×10^{-6})⁵. A leak caused by moving TC can occur if (i) handling is rough or (ii) deterioration is high.

(i) In order for a TC to leak while being handled, both of the following events must occur “Failure to follow the SOP” and “Sufficient roughness to cause a leak”. These are a human error and an equipment failure and therefore have a probability of 1×10^{-3} .

(ii) High deterioration of TC can be a combination of change in environment which would speed up the process and failure to detect through inspection. These are a human error and an equipment failure and therefore have a probability of 1×10^{-3} .

3. Release of agent due to explosion or fire. From Figure 1 of Appendix B, one of the following event must occur to result in an explosion or fire: 1) Automobile crash (probability: 6×10^{-5} , or 2) Transporting vehicle catches on fire or explodes. Fire or explosion of transport vehicle can happen if a combination of the following three events occur: “Failure to inspect the vehicle”

(Human error probability: 1×10^{-3}), “Component failure” (Equipment failure probability: 1×10^{-3}), and “Failure sufficient to cause fire or explosion” (probability: 2.8×10^{-4})⁵.

4. Release of agent due to mechanical forces generated in a vehicle accident (not shown in fault tree). Two events must occur in order for this to happen: 1) Truck is in an accident (1×10^{-4}), and 2) Leak occurs due to the accident (1.2×10^{-4})⁵.

The probability of each of the 4 main subevents is therefore:

1. TC Dropped Releasing Agent	2.81×10^{-6}
2. Leak of Agent From TC	6.90×10^{-6}
3. Release of Agent Due to Fire or Explosion	6.00×10^{-11}
4. Release of Agent Due to Mechanical Forces/Accident	1.20×10^{-11}

NOTE: Since the probability of last event was not credible, it was left out of the fault tree. The third event was depicted in the fault tree because if this event were credible, it would provide the longest downwind hazard (result of mustard on fire).

The overall calculated probability of having a release of agent from a TC during transport is 9.71×10^{-6} as shown in Figure 1 of Appendix B. From Table 4 of Appendix C, this probability is categorized as **E, improbable**⁶.

Severity. The severity was based on the credible subevent which involved the largest release of agent. This is assumed to be a rupture of the ton container spilling the entire contents of the TC (1700 lb.). Using the assumptions above and this amount of agent, the D2PC downwind prediction program⁷ calculated a 1% lethality distance of 31 meters and a No effects distance of 541 meters. This presents a danger to personnel on post but not off post (Unless the release occurs in Bush River Storage Area. The No effects downwind arc extends approximately 400 feet into the Bush River.). Therefore, because of the on-post hazard, the severity of this consequence is categorized as **I, catastrophic**⁶.

Risk. The risk associated with transporting 1 ton container from CASY to the CTF is I-E, catastrophic-improbable. According to military guidance, the risk level is **MEDIUM**.

Risk of transporting 3 ton containers on a single truck.

Probability. Using the same fault tree and changing probabilities of bottom events based on 3 ton containers instead of 1 TC, the probability of a release from a TC during the transport of 3 TCs on a single truck was calculated. Though investigation it was determined that the only

probability that would change from the 1 TC move is a slightly higher risk of mechanical failure. However, this increase is not enough to change the improbably to remote, thus not significantly effecting the risk.

Severity. The severity was based on the credible subevent which involved the largest release of agent. This agent is a rupture of the ton container spilling the entire contents of the TC (1700 lb.). However, since this task is performed one at a time, the severity does not change.

Risk. The risk associated with transporting 3 ton containers from CASY to the CTF is I-E, catastrophic-improbable. According to Figure 2 of Appendix C (ref. 3e), the risk level is MEDIUM.

Risk of transporting 9 ton containers on 3 trucks (3 TCs per truck).

Probability. Since we have determined the probability of release of 1 ton container from a single truck of 3 TCs, the probability of release of 1 TC from 3 trucks with 3 TCs is simply 3 times the former probability (2.91×10^{-5}), or 8.73×10^{-5} . This probability is categorized as E, improbable.⁸

Severity. The severity does not change since a rupture of the ton container that releases is still credible and a fire is not credible. Therefore, the severity of this consequence is based on the same downwind release and is categorized as I, catastrophic⁶.

Risk. The risk associated with transporting 9 ton containers from CASY to the CTF is I-E, catastrophic-improbable. According to Figure 2 of Appendix C (ref. 3e), the risk level is MEDIUM.

CONCLUSION.

All of the scenarios examined have the same chemical risk, MEDIUM. The scenario of hauling 9 ton containers at once is the most timely while maintaining the lowest possible risk.

RECOMMENDATION.

Move 27 ton containers in three convoys consisting of 9 TCs on 3 trucks (3 TCs per truck) from the CASY to the CTF for sampling. (Chemical risk: MEDIUM)

5. CONCLUSION

The use of fault trees has added to the effectiveness of the Edgewood Safety Office. Fault trees have proved themselves as a valuable tool in minimizing risk and extremely useful in conveying the risk to both workers and management. The ease of use and the effectiveness of the graphical presentation makes fault trees better than most every other hazard analysis.

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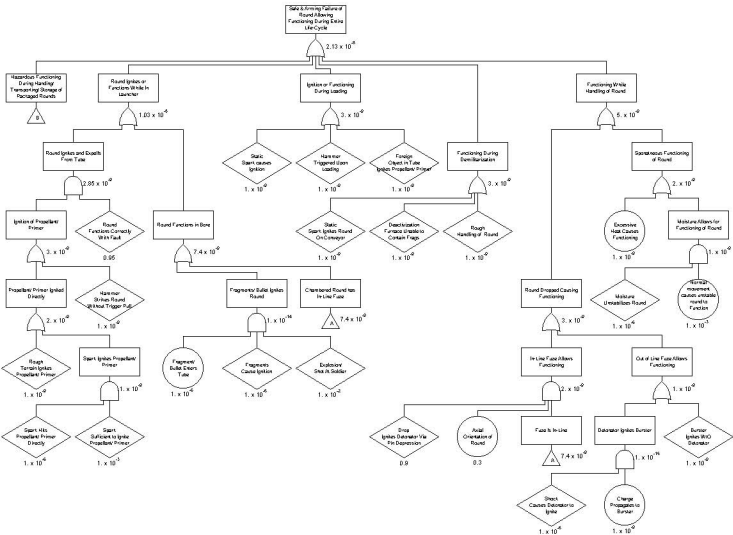
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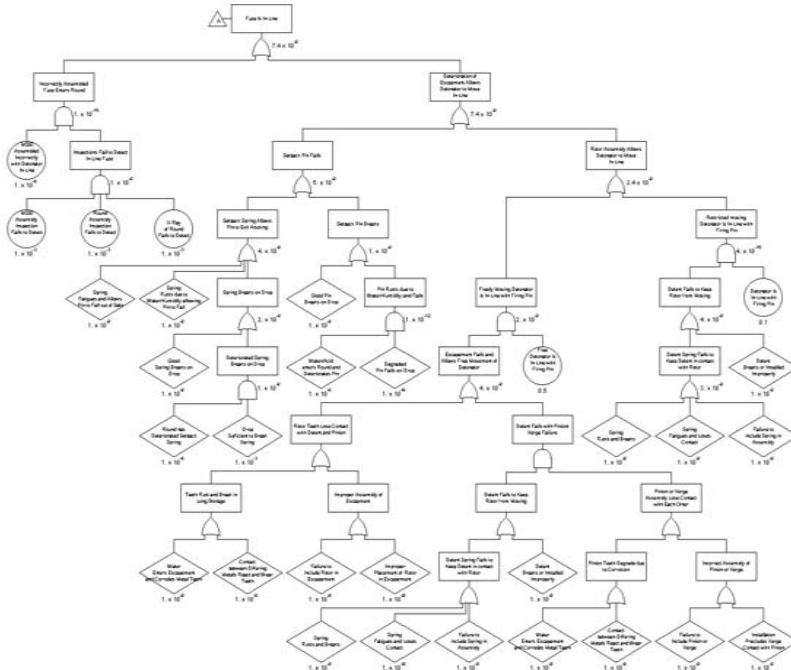
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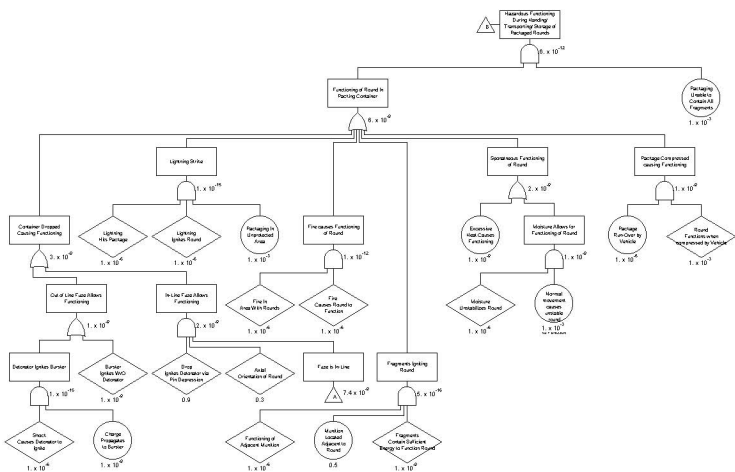
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Appendices

- A. Fault Tree for XM998 Smoke Grenade
- B. Fault Tree for Transporting Ton Container
- C. Risk Assessment Codes







Moving One TC from CASY Fault Tree Diagram

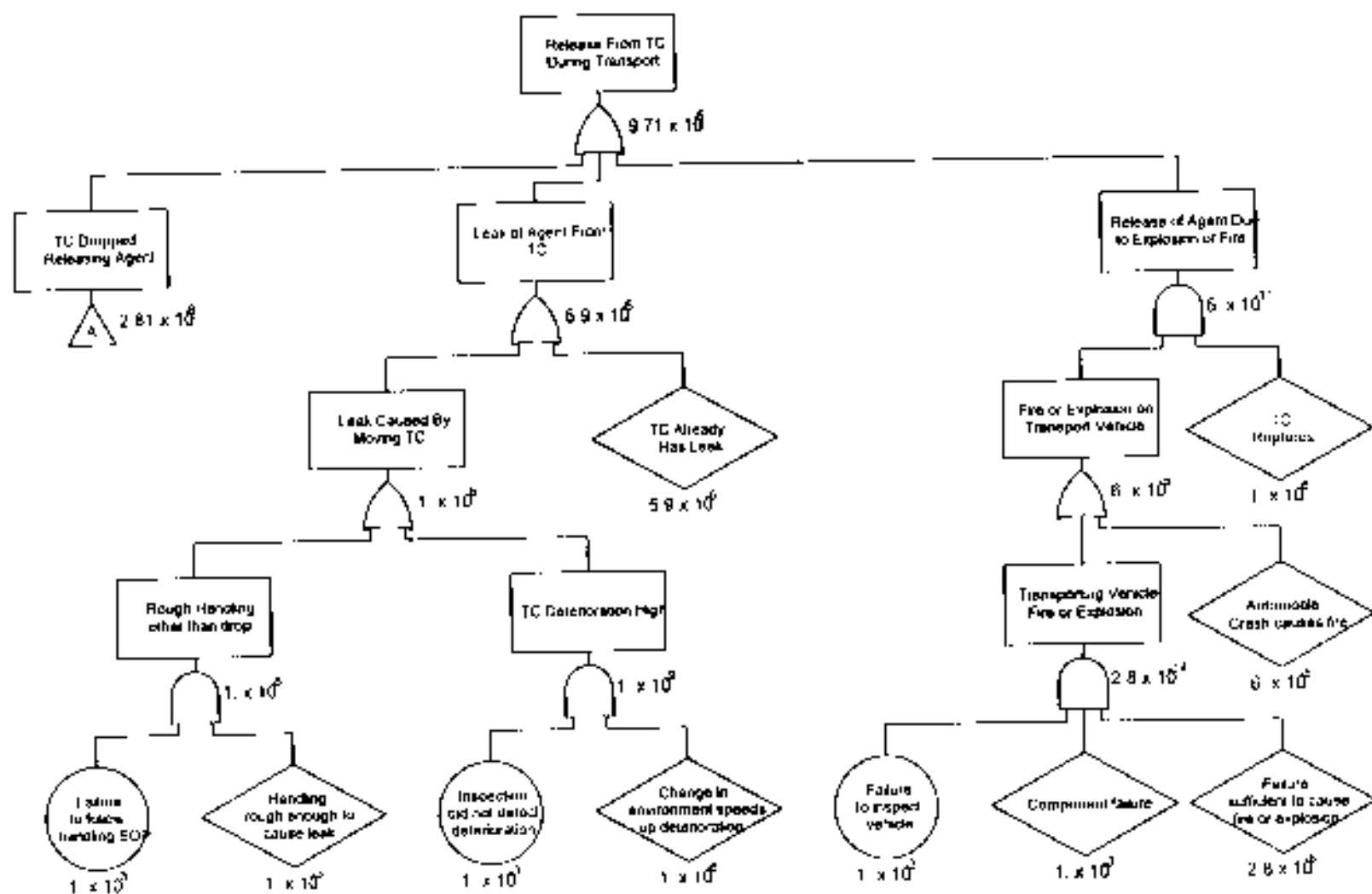
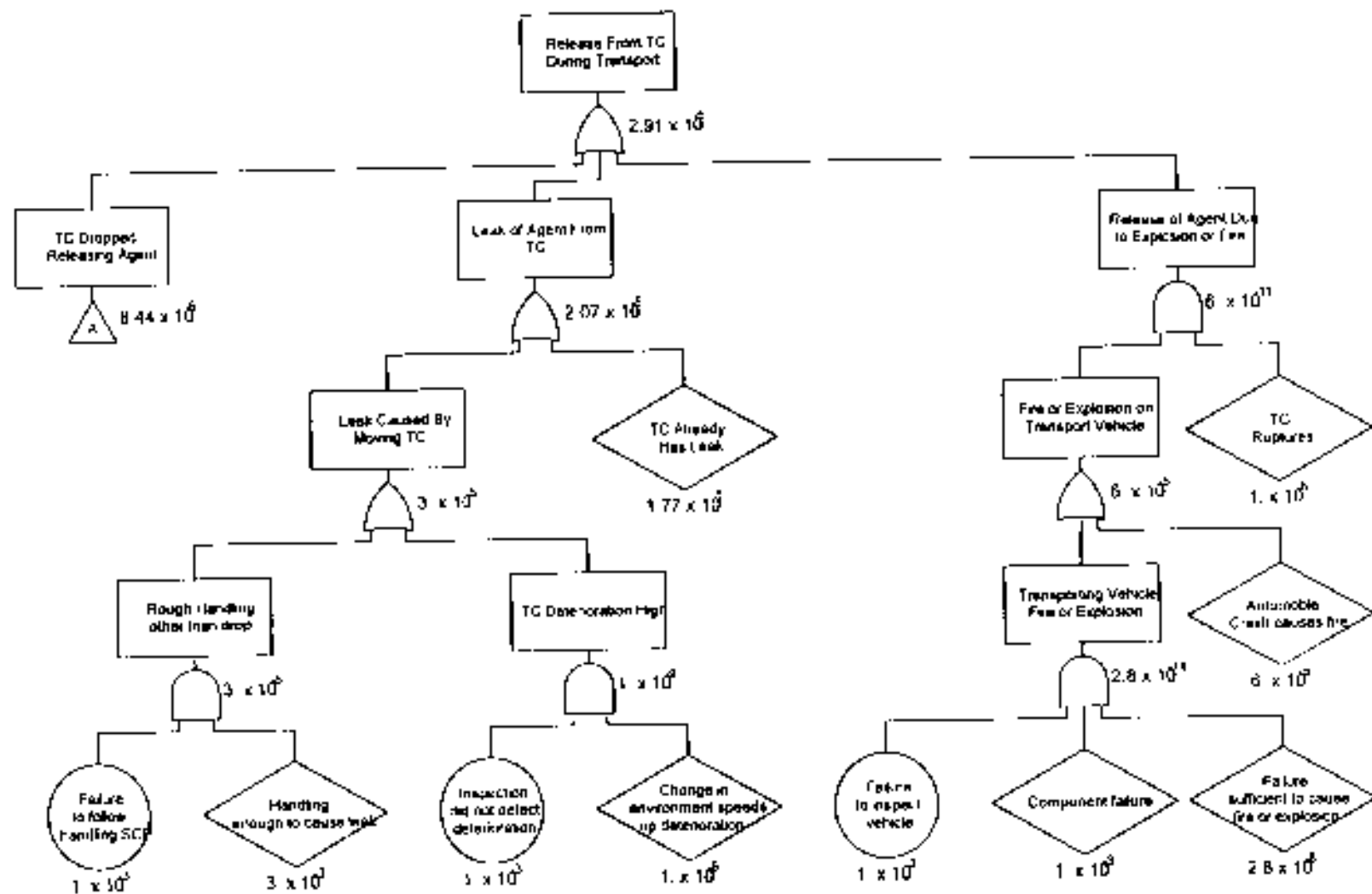


Figure 1

Moving Three TCs on Truck from CASY Fault Tree Diagram



APPENDIX B (cont.)

Figure 3

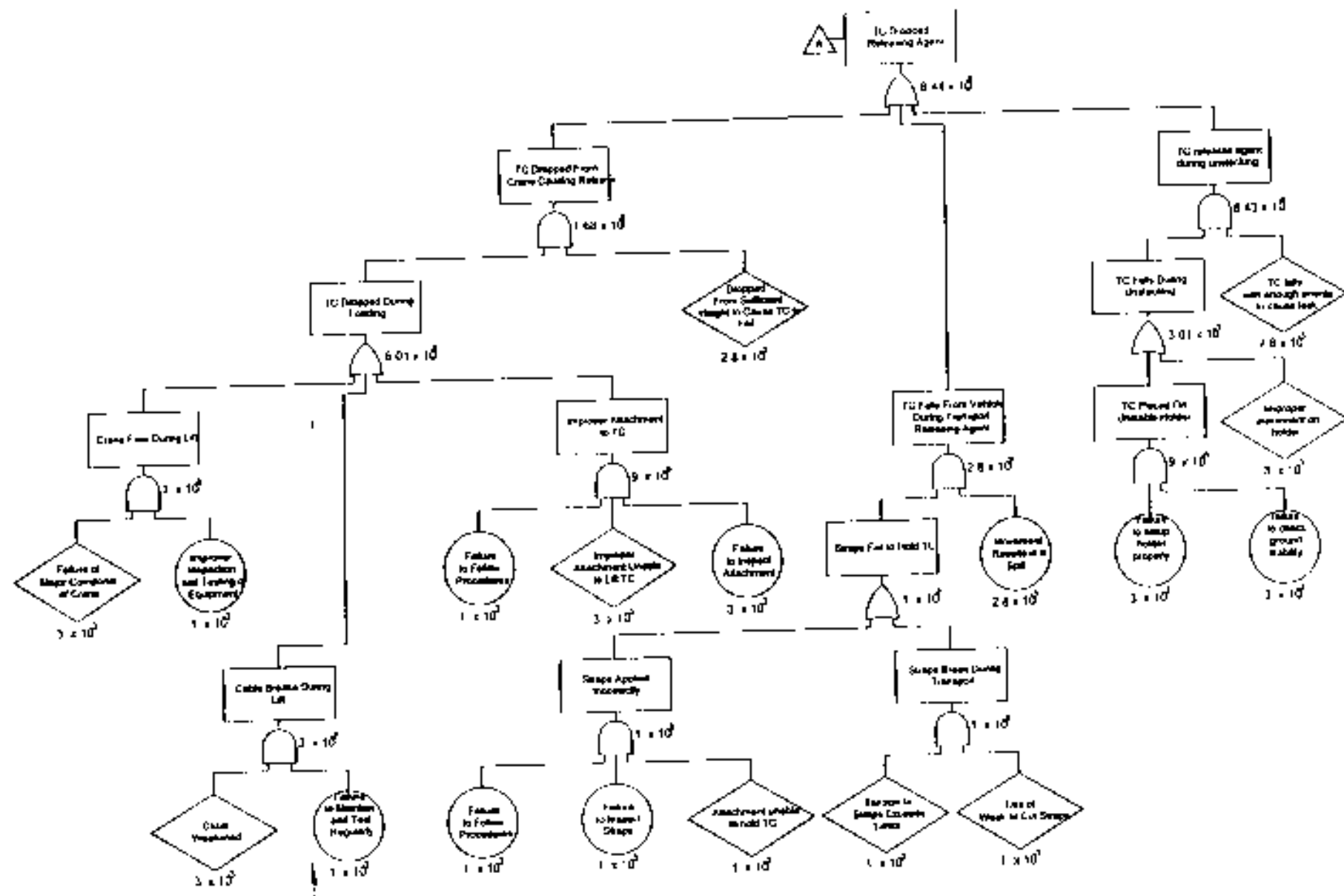


Figure 4

Appendix C. Risk Assessment Codes¹⁵

Risk Assessment Code Matrix					
Hazard Severity	Frequent A (1.0-10 ⁻²)	Probable B (10 ⁻² -10 ⁻⁴)	Occasional C (10 ⁻⁴ -10 ⁻⁶)	Remote D (10 ⁻⁶ -10 ⁻⁷)	Improbable E (10 ⁻⁷ -0)
I - Catastrophic	1	1	2	2	3
II - Critical	1	2	2	3	4
III - Marginal	2	3	3	4	4
IV - Negligible	3	3	4	4	4

Hazard Severity

I	Catastrophic	May cause death or loss of a facility.
II	Critical	May cause sever injury, sever occupational illness, or major property damage.
III	Marginal	May cause minor injury or minor occupational illness resulting in lost workday(s), or minor property damage.
IV	Negligible	Probably would not affect personnel safety or health and thus, less than a lost workday, but nevertheless is in violation of specific criteria.

Mishap Probability

A	Frequent (10 ⁻² -1.0)	Likely to occur frequently in life of system, item, facility, etc.
B	Probable (10 ⁻⁴ -10 ⁻²)	Will occur several times in the life of a facility or operation.
C	Occasional (10 ⁻⁶ -10 ⁻⁴)	Likely to occur sometime in the life of a facility or operation.
D	Remote (10 ⁻⁷ -10 ⁻⁶)	Unlikely but possible to occur in the life of facility or operation.
E	Improbable (0-10 ⁻⁷)	So unlikely it can be assumed occurrence may not be experienced.

Hazard Risk Index	Risk Assessment Code	Risk Level
IA,IB,IIA	1	Extremely High
IC,ID,IIB,IIC,IIIA	2	High
IE,IID,IIIB,IIIC,IVA,IVB	3	Medium
IIIE,IIID,IIIE,IVC,IVD,IVE	4	Low